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# Decoding the Message from Meteoritic Stardust Silicon Carbide Grains

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**Abstract.** SiC mainstream grains are presolar grains believed to form in the envelopes of carbon rich asymptotic giant branch (AGB) stars with masses between 1.5 and 3 solar masses. These grains represent a conundrum as the  $^{29}\text{Si}$  and  $^{30}\text{Si}$  abundances indicate that they formed in stars of super-solar metallicity, before the solar system formed. To shed light on this problem, we use silicon isotopic abundances to derive an age-metallicity relation for the stars believed to have produced the SiC mainstream grains. For 2732 mainstream SiC grains listed in the Presolar Grain Database, we use the  $^{29}\text{Si}$  abundances with the latest galactic chemical evolution (GCE) models to derive  $[\text{Fe}/\text{H}]$ , and  $^{30}\text{Si}$  abundances along with the models of Zinner et al. (2006) to determine an approximate birth age for the parent AGB star. Comparing our age-metallicity relation with observational relationships derived for nearby stars, we find that the spread of  $[\text{Fe}/\text{H}]$  is in agreement, but the mean  $[\text{Fe}/\text{H}]$  in our relation is higher by 0.2 dex. We propose that this difference is because stars with higher  $[\text{Fe}/\text{H}]$  produce more dust and thus are over-represented in our age metallicity diagram, a finding consistent with previous published works. This result offers a solution for the long-standing problem of silicon in stardust SiC grains, confirms the necessity of coupling chemistry and dynamics in simulations of the chemical evolution of our Galaxy, and constrains the modelling of dust condensation in stellar winds as a function of the metallicity.

**Keywords:** dust, extinction – meteorites, meteors, meteoroids – Galaxy: abundances – stars: AGB and post-AGB.

**PACS:** 26.20.Kn, 97.10.Cv, 98.35.Bd, 98.35.Ac & 96.30.Za.

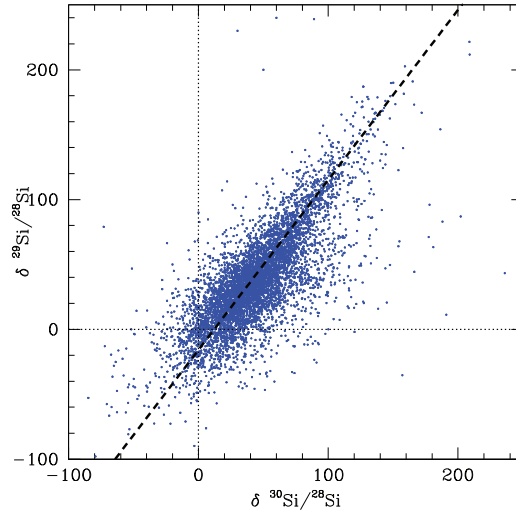
## INTRODUCTION

In the late 1980s it was found that a small fraction (1-100 parts per million) of the matrix of primitive meteorites was comprised of stardust grains. As a result of their isotopic abundances, these grains are thought to have been formed in stars, and subsequently transported through the interstellar medium (ISM) where they could be incorporated into the proto-solar nebula, and later, meteorites. As the isotopic composition of these grains gives clues on their formation environment and subsequent processing, these grains have been used to investigate such diverse topics such as nucleosynthesis and mixing in stars, dust formation and processing in the ISM as well as galactic chemical evolution (e.g. Bernatowicz & Zinner, 1997; Clayton & Nittler 2004).

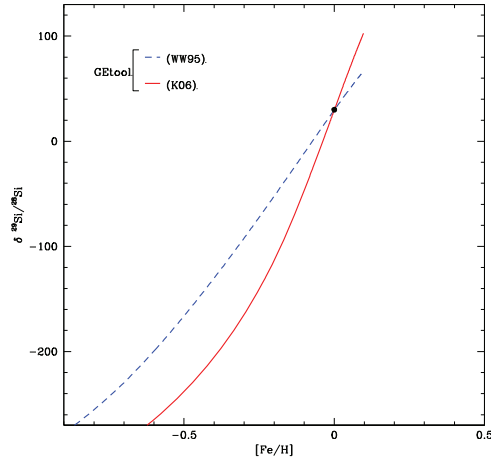
While many different minerals have been found as stardust grains, including  $\text{Al}_2\text{O}_3$ , diamond and silicates, one of the most studied types is silicon carbide stardust grains. This focus on these types of grains is partially due to their larger size and partially due to their relatively simple separation procedure. A majority of SiC stardust grains are thought to have originated in the envelope of carbon-rich asymptotic giant branch (AGB) stars (Galino et al. 1990; Lugaro et al. 2003). As the star proceeds up the AGB, subsequent third dredge up episodes bring fresh carbon from the ashes of the burning shell to the envelope. When the carbon abundance in the envelope exceeds the oxygen abundance, free carbon becomes available to form these carbon-rich grains (as carbon and oxygen preferentially combine to form CO). In addition, the elemental and isotopic abundances found in these grains indicate a degree of s-process isotope enrichment, which is in agreement with that calculated to occur in stars. In particular,  $\sim 93\%$  of SiC grains, the “mainstream” population, in addition to the Y and Z grains, each comprising 1% of the grain population, are thought to form in these C-rich AGB stars. Specifically, it is thought that Y and Z grains come from stars with metallicity approximately one half and one third solar respectively, while mainstream grains come from stars of approximately solar metallicity (Hoppe et al. 1997; Amari et al. 2001; Zinner et al. 2006). For the remainder of this work we focus on mainstream grains.

A large amount of silicon isotopic data has been measured for these SiC mainstream grains since their discovery. One of their more puzzling properties is that SiC mainstream grains generally have higher  $^{29}\text{Si}/^{28}\text{Si}$  and  $^{30}\text{Si}/^{28}\text{Si}$  abundances than the Sun (see figure 1). This is especially unexpected as  $^{28}\text{Si}$  is a primary isotope while  $^{29}\text{Si}$  and  $^{30}\text{Si}$  are secondary isotopes, so the ratio of  $^{29}\text{Si}/^{28}\text{Si}$  and  $^{30}\text{Si}/^{28}\text{Si}$  would be expected to increase with time (Timmes &

Clayton 1996), so it would be naively expected that SiC grains formed in stars that were born before the Sun would have lower ratios than the Sun. A range of possible explanations have been proposed for this problem, including migration of metal-rich stars from the inner part of the galaxy (Clayton 1997), inhomogeneities in the ISM (Lugaro et al. 1999) and a starburst due to a galaxy merger (Clayton 2003). However all of these models have difficulty successfully reproducing the data (e.g. Nittler & Alexander 1999; Nittler 2005). In this work we take an alternative approach and use the Si isotope ratios of the grains to estimate the properties of the stars in which they were formed, and compare those properties to the measured properties of stars in the local solar neighbourhood.



**FIGURE 1.** Si three isotope plot for SiC mainstream grains (blue points). The mainstream line (black dashed) shows the best fit to the mainstream grains and has slope 1.31 and intercept -15.9 per mil.

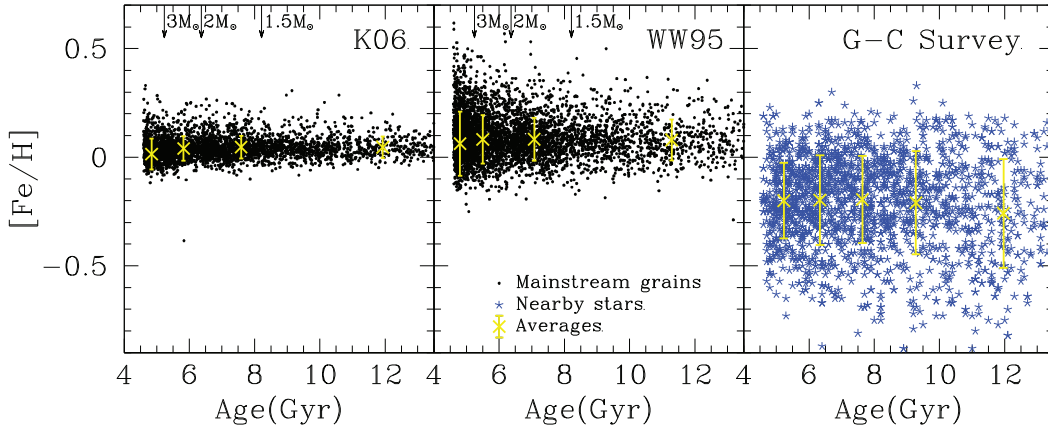


**FIGURE 2.** Calculated relationship between  $\delta^{29}\text{Si}$  and  $[\text{Fe}/\text{H}]$ , derived using GETool (Fenner & Gibson 2003) with yields from Woosley & Weaver (1995) (WW95) and Kobayashi et al. (2006) (K06) (see text for details).

## METHOD

From the Presolar Grain Database (Hynes & Gyngard 2009) we selected the 2732 mainstream grains with one sigma errors less than 15 per mil and conducted the following steps:

1. Use the  $\delta^{29}\text{Si}$  abundance to infer the metallicity  $[\text{Fe}/\text{H}]$  of the host star using the relationship predicted between  $\delta^{29}\text{Si}$  and  $[\text{Fe}/\text{H}]$  by Galactic Chemical Evolution (GCE) models. As these models did not match solar composition at the time of the Sun's birth (4.5 Gyr), these models were renormalized such that the Sun had  $\delta^{29}\text{Si}=0$  and  $[\text{Fe}/\text{H}]=0$  by definition (see figure 2).
2. The change in  $\delta^{30}\text{Si}$  was estimated as follows. First, a "shifted" mainstream line, representing the stellar abundance before third dredge up, was calculated by taking the mainstream line and moving it -15 per mil in the  $\delta^{30}\text{Si}$  direction. This shift was chosen as it matches the distribution of O-rich silicate grains (Mostefaoui & Hoppe 2004; Nguyen et al. 2010). The change in  $\delta^{30}\text{Si}$  was then estimated by the difference between the grain  $\delta^{30}\text{Si}$  value, and that of the shifted line.
3. The star mass (and thus age) was determined by combining the change in  $\delta^{30}\text{Si}$  with the  $[\text{Fe}/\text{H}]$  and comparing to results from FRANEC stellar AGB models run using the neutron capture cross-sections from Guber et al. (2003) and presented in Zinner et al. (2006).
4. As AGB nucleosynthesis can also affect  $\delta^{29}\text{Si}$ , the process described in steps 1-3 was repeated, but using a new initial  $\delta^{29}\text{Si}$  abundance derived from the AGB model predictions used to determine the stellar mass. The results were similar.



**FIGURE 3.** Age-metallicity relation derived for grain parent stars using GCE models calculate using GETool, with yields from Woosley & Weaver (1995) (WW95) and Kobayashi et al. (2006) (K06), compared with the observed local solar neighbourhood age-metallicity relation from the Geneva-Copenhagen survey (Holmberg et al. 2007).

## RESULTS AND DISCUSSION

We plot our derived SiC age-metallicity relation (AMR) in figure 3 alongside that for stars in the solar neighbourhood from the Geneva-Copenhagen Survey (Holmberg et al. 2007). We describe the sources of error in our age and metallicity determination and then discuss these results in terms of dust formation efficiency.

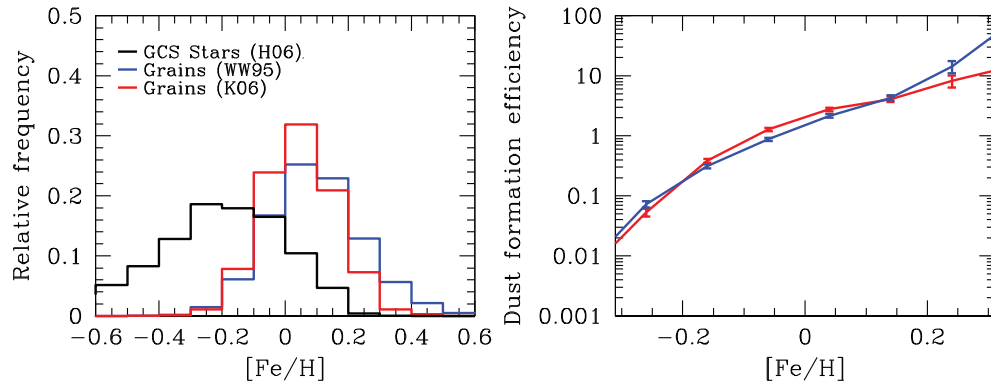
### Sources of Errors in SiC Star Ages

The derived SiC ages have uncertainties originating from a number of sources. First SiC grains can form during the entire time for which a star is carbon rich. While there are a range of Si isotopic compositions during this period, a majority of the mass loss occurs during the last few thermal pulses, for example, for the three solar mass models of

Straniero et al. (1997), two thirds of the envelope mass loss during the carbon rich phase occurs during the last two thermal pulses. So, while a few grains may form during the first thermal pulses for which the star is carbon rich, the assumption that the final silicon isotope composition is representative for all grains produced by a given star, will be more or less correct for a majority of grains. Second, there are errors in the grain measurements themselves. To minimize these errors, we only analysed grains with small measurement errors. Third, the assumption of one silicon isotopic composition corresponding to one metallicity and stellar mass may not be correct due to the effect of inhomogeneities in the ISM. Such inhomogeneities may be capable of altering star compositions by up to 50 per mil (Lugaro et al. 1999; Nittler 2005). While this error means that the  $\delta^{30}\text{Si}$  values, and thus the ages for individual grains are likely to be wrong, as the effect is isotropic, the peak of the grain distribution should be relatively unaffected. Third, a range of shifted mainstream lines would be in agreement with the silicate grain data due to the large error bars. For example, a line shifted further from the mainstream line would lead to smaller calculated ages, but could still be in agreement with the silicate data. Fourth, stellar model uncertainties due to, for example, third dredge up efficiency and neutron capture crosssections may result in either larger or smaller stellar ages. Finally, these calculations do not account for the residence time of the grain in the ISM which may be up to 1 Gyr (Gyngard et al. 2009; Gyngard, this proceedings).

### Sources of Errors in SiC Star Metallicities

The slope of the  $\delta^{29}\text{Si}$  vs  $[\text{Fe}/\text{H}]$  line calculated from the GCE models determines the amount of scatter in calculated metallicity. For example, the slope for the case of the Kobayashi et al. (2006) yields is high, resulting in a small spread, while that for the Woosley & Weaver (1995) yields is lower, resulting in a larger spread. For this work we used models calculated using the GCE model GETool (Fenner & Gibson 2003) computed using dual infall, a Kroupa et al. (1993) stellar initial mass function, a Schmidt-Kennicutt star formation prescription, and tuned to match Milky Way gas and stellar abundances, as well as surface density. From figure 3, the observed age metallicity relation for nearby stars is very flat, a factor which none of the models can completely match. As discussed in Lewis et al. (2013), one possible way to address this mismatch is to update current models such that they combine galactic dynamics and chemical evolution (Kobayashi & Nakasato 2011; Pilkington et al. 2012), in particular, updating such models to track isotopic rather than elemental abundances. Despite this, grain data and observational data agree that stars born before the Sun exist that have metallicity higher than the Sun.



**FIGURE 4.** Calculated metallicity distribution function for grain parent stars, using GETool, and yields from Woosley & Weaver (1995) (WW95) and Kobayashi et al. (2006) (K06), compared with that from the Geneva-Copenhagen survey (GCS). In the right panel we show the calculated SiC relative dust formation efficiency.

### Relationship Between SiC Dust Formation and Metallicity

We investigated the metallicity distribution function (MDF) calculated from mainstream grains, and in particular compared it with that of Geneva-Copenhagen survey stars from Holmberg et al. (2007) (see figure 4). As the error

in the calculated metallicity due to grain measurement error, less than 0.03 dex, is so much smaller than the observational error for the stars, approximately 0.1 dex, we convolve the grain distribution with a 0.1 dex gaussian. As can be seen in figure 4, the distribution of metallicities of measured stars and derived star metallicities from SiC grains are offset by approximately 0.2 dex. One explanation is that SiC dust forms more efficiently in the envelopes of metal-rich stars. This conclusion is supported by Spitzer mid-IR observations of AGB stars in the small and large magellanic clouds, which found that emission from SiC dust increases with increasing metallicity (Sloan et al. 2008). To quantify this effect in our results we calculate the relative likelihood that a grain will be produced at a given metallicity, the dust formation efficiency (see figure 4). This relationship is only valid for  $[\text{Fe}/\text{H}]$  between -0.3 and +0.3 as this is where there are sufficient numbers of stars and grains for this result to be meaningful.

## CONCLUSIONS

Our results:

- Support the finding that the galactic age-metallicity distribution is flat and that there is spread of metallicity at each age.
- Support the idea that SiC dust formation efficiency increases as metallicity increases.

In addition, improvements in GCE modeling, for example, including the effects of coupling chemical evolution and dynamics (Kobayashi & Nakasato 2011; Pilkington et al. 2012), as well as additional measurements of grains, in particular silicate stardust grains, could allow for future improvements on these results.

## ACKNOWLEDGMENTS

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